

## ACCOMPLISHMENT REPORT

### PROPULSION DIRECTORATE

April 2000

TITAN IV ROCKET MOTOR VALIDATION TEST SUCCESSFUL: A Titan IV Solid Rocket Motor Upgrade (SRMU) booster featuring a new nozzle material was successfully fired on 19 March 2000. This motor firing took place at the Propulsion Directorate's Test Stand 1-C at Edwards AFB, California. The purpose of this test was to provide data and validate the performance of new, environmentally compliant materials used to manufacture the SRMU's carbon-carbon nozzle. The new materials were manufactured in an environmentally sound manner, and they replace materials that are no longer compliant or available under current regulations. During this successful test, which lasted for approximately 140 seconds, the 11-story high, 750,000 pound SRMU booster generated some 1.7 million pounds of thrust! The Titan IV SRMU was developed to enhance the performance of the nation's largest heavy lift space launch vehicle, and its addition has increased the Titan IV system's lift capability by 25 percent while improving reliability. The Titan IV's launch propulsion system consists of two SRMUs in combination with the liquid-fueled core launch vehicle. This was the first Titan IV testing accomplished at Test Stand 1-C since 1993. Since that time, the Titan IV has been used for numerous space launches. (L. Quinn, AFRL/PRR, (661) 275-5630)

[An Air Force press release on this accomplishment is available at [http://www.af.mil/news/Apr2000/n20000404\\_000514.html](http://www.af.mil/news/Apr2000/n20000404_000514.html)]



The recent SRMU booster firing at Test Stand 1-C (left) and a Titan IV on the launch pad (right)

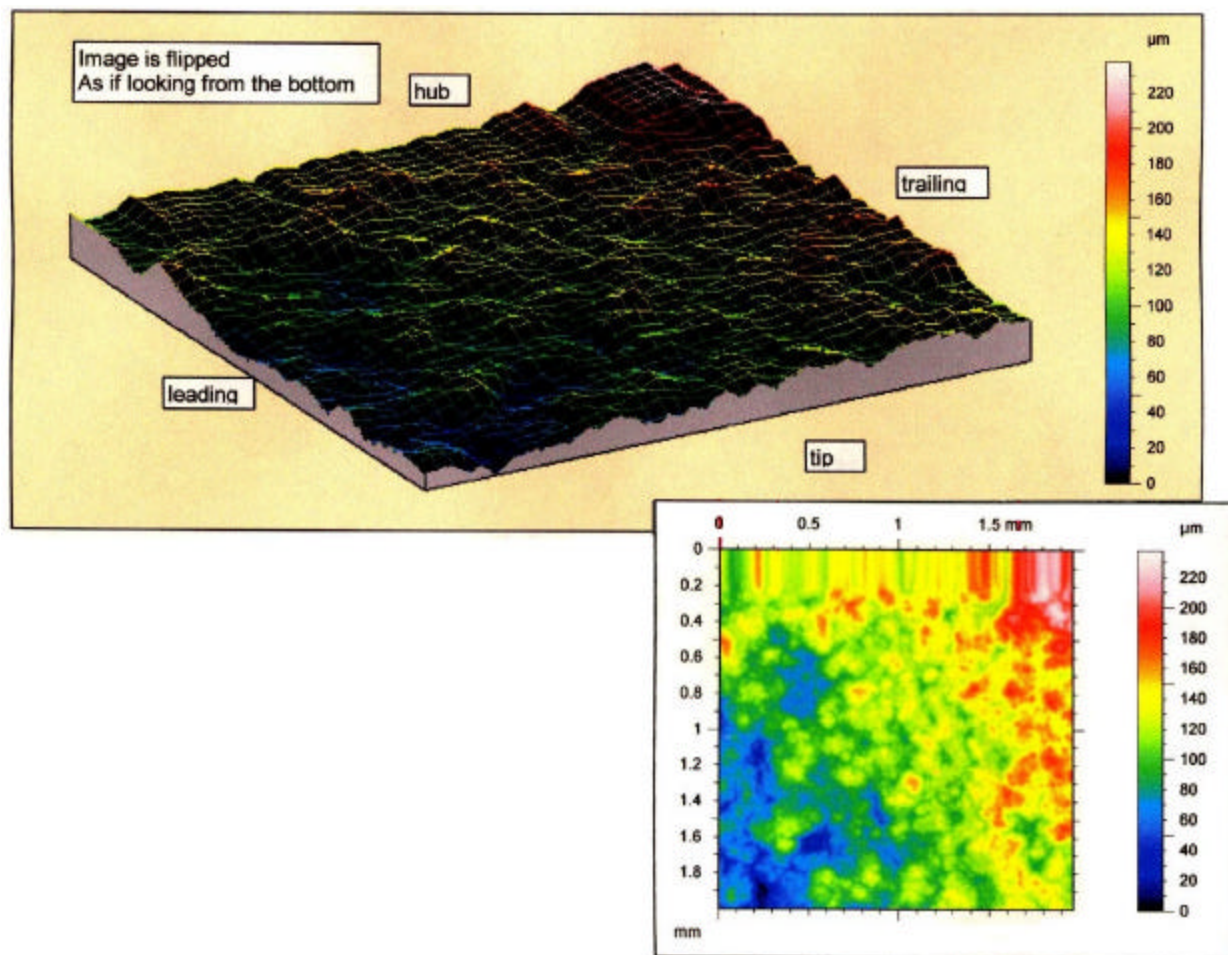
CARBON-CARBON PROCESS PASSES ENVIRONMENTAL TESTS: The Propulsion Directorate's Propulsion Materials Applications Branch (AFRL/PRSM) has taken a major step towards commercializing their in-situ carbon-carbon densification process. With its eye on commercialization of this process, PRSM tasked Parsons Engineering with developing a thorough understanding of any potential health hazards associated with the process. Parsons Engineering recently completed their assessment with very encouraging results. The abatement techniques applied by PRSM satisfy all state requirements for particulate and Volatile Organic Compound (VOC) emissions. The emissions from the vent line fall well within state guidelines, and in the opinion of Parsons Engineering, satisfy Best Available Control Technology (BACT) and Best Available Control Technology for Toxics (TBACT) requirements. Even assuming VOC emissions an order of magnitude higher than they presently are, the health risk assessment was within the permitted range. The in-situ densification process is a liquid phase route to producing high-quality, machinable, carbon-carbon composites. The in-situ process is an attractive alternative to traditional Chemical Vapor Infiltration (CVI) because the processing time and cost are a fraction of those required by CVI. Markets for this technology reside mainly in the aerospace community, and parts manufactured using the process include rocket nozzles, aircraft brakes, and fasteners. With further cost reductions, materials manufactured by this process may find substantial markets in consumer products such as sporting goods. (K. Chaffee, AFRL/PRSM, (661) 275-6170)



A carbon-carbon tube produced in support of the F-22 program (left) and leading edges produced in support of the Hyper-X program (right)

MEASUREMENT OF ROUGHNESS EFFECTS ON TURBINE HEAT TRANSFER: Researchers in the Propulsion Directorate's Turbine Branch (AFRL/PRTT), in collaboration with AFIT and the University of Mississippi, are conducting a DoE funded study on the effect of roughness on turbine blade heat transfer. As turbine blades wear, their surface finishes can change significantly. Newly manufactured blades have a smooth, near-mirror finish, while blades that have seen significant use can be very rough as a result of pitting, erosion, flaking of thermal barrier coating (TBC), spallation, and fuel deposits. This variation in roughness can lead to significant changes in both aerodynamics and heat

transfer characteristics. Of significant interest is the effect of roughness on heat transfer, since modern blades are designed with very little thermal margin. In order to meet life goals, the designer must understand not only the as-installed heat transfer characteristics but also how those characteristics change with use. Unlike previous studies, in which roughness was represented by idealized elements such as spheres or cones, the current research is being performed using surfaces that are scaled up three-dimensional (3D) models of actual turbine blade surfaces. Several manufacturers have loaned hardware for examination so accurate measurements of realistic surfaces can be made. Magnified sample surfaces have been created using a 3D printing machine installed in a boundary layer tunnel in the Turbine Aerothermal Research Facility. Initial aerodynamic data is now being collected, and heat transfer data will be collected this summer. Subsequent efforts will compare experimental data with numerical results from models being developed at the University of Mississippi. (R. Sondergaard, AFRL/PRTT, (937) 255-6768)



Sample surface topology measurements

**SUPERCONDUCTIVITY RESEARCH PROVIDES BREAKTHROUGH:** A cooperative research effort between the Propulsion Directorate's Superconductivity Group (AFRL/PRPS), the Materials Directorate (AFRL/MLPO), and the University of Wisconsin Applied Superconductivity Center

recently led to an important discovery in the field of superconductivity. A previously unknown grain boundary effect in high-temperature superconductor (HTS) coated conductors was discovered. This effect in the HTS coating, resulting from the underlying substrate grain boundaries, has a very strong influence on the critical current that the HTS film can carry. International experts cited this information as “crucial” at invited talks this past fall in America and Europe. With knowledge of this effect, industry can now work toward correcting grain alignment in the substrate material. This discovery will drastically shorten the time needed to develop the long lengths of coated conductor needed for HTS power generators and magnets. In turn, this will hasten the deployment of new Air Force systems such as directed energy weapons. Results of this joint effort are being submitted for initial journal publication in *Nature*, and the AFRL/PRPS Superconductivity Group was named the Propulsion Directorate’s Project of the Quarter for this achievement. (P. Barnes, AFRL/PRPS, (937) 255-2923)

FIVE PR RESEARCH GROUPS NAMED AFOSR STAR TEAMS: Five research groups in the Propulsion Directorate were recently recognized as Air Force Office of Scientific Research (AFOSR) Star Teams. Of these five teams, two received renewals of their Star Team status. The High Energy Density Matter (HEDM) team, led by Dr. Jeffrey Sheehy, had their Star Team status renewed for a term of two years. The HEDM team was first awarded Star Team status in 1990 and has held that status continuously ever since. The Advanced Plume Studies Research team, led by Dr. Ingrid Wysong, received a three-year renewal. This is the third renewal for this group, with the first two terms coming under the leadership of the late David Weaver. The long-standing Star Team status of the HEDM and Advanced Plume Studies teams marks them as two of the Air Force’s premier research groups. Three additional PR research teams were named AFOSR Star Teams for the first time, each for a term of two years. These new teams are the Advanced Supercritical Fuels/Supercritical Combustion team, the High Temperature Superconductor (HTS) Materials for Advanced Power Systems team, and the Inorganic Synthesis team. Drs. Tim Edwards, Paul Barnes, and Shawn Phillips, respectively, lead these new Star Teams. (J. Pearce, AFRL/PRO (UTC), (937) 255-5451)

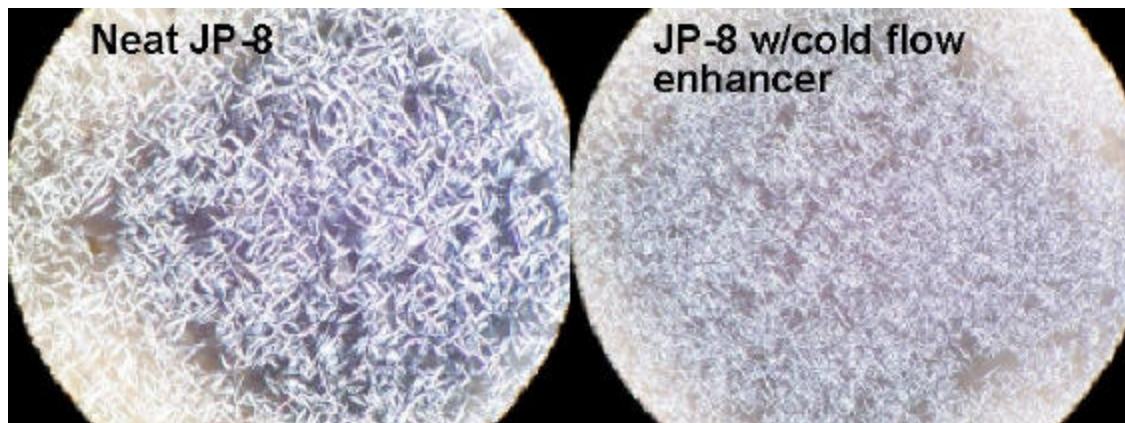


The U-2 reconnaissance aircraft

JPTS, the fuel used by the U-2 reconnaissance plane, with a more economical alternative. The approach being pursued is to alter the low temperature properties of JP-8+100 using additives. Due to

NEW COLD FLOW FUEL LAB OPERATIONAL: Researchers in the Propulsion Directorate’s Fuels Branch (AFRL/PRSF) recently opened a new cold flow fuel laboratory at Wright-Patterson AFB, Ohio. Both the cold stage microscope and the fundamental fuel wing tank simulator are housed in this laboratory. This new laboratory was created to support efforts to develop a new low temperature fuel known as JP-8+100 LT (LT for low temperature). Development of this fuel was catalyzed by a desire to replace

the cost difference between JP-8 and JPTS, this approach promises to reduce U-2 fuel cost by as much as 80 percent. Work to transition this new fuel to the operational Air Force is already under way. Representatives of AFRL/PRSF recently met with personnel from San Antonio Air Logistics Center (SA-ALC), Warner Robins Air Logistics Center (WR-ALC), and C4E (Consulting for Energy Efficiency and Environmental Excellence, Inc) to begin planning the transition of this new fuel to the field. Primary issues for the transition include converting bases that already have JPTS to JP-8+100 LT, using the LT additive as part of a deployment, and the availability of the LT additive at all bases. One possibility being considered for distribution of the LT additive is to create an additive “cocktail” that combines the LT additive with the +100 thermal stability additive package. (Lt K. Wohlwend and C. Obringer, AFRL/PRSF, (937) 255-3190)

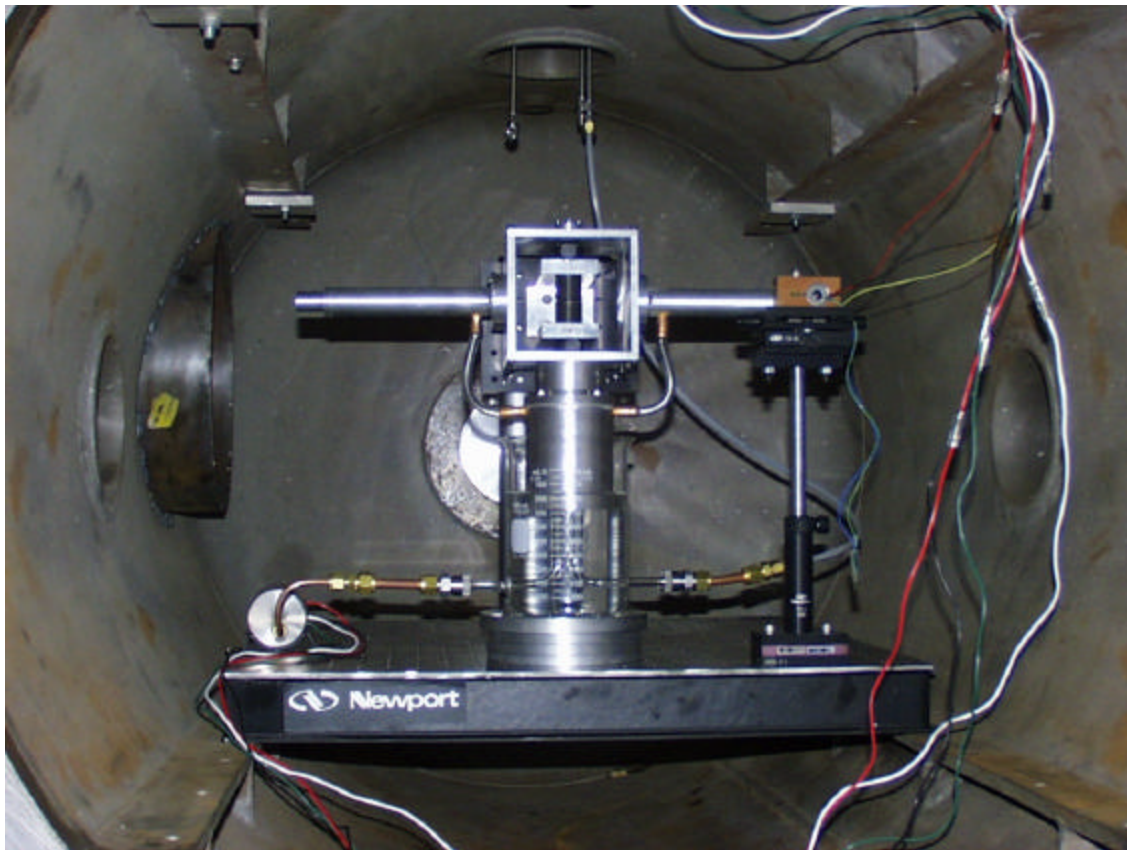


Microscope studies showing the effect of the cold flow enhancer on frozen JP-8

**SUPPORT FOR NAVY THEATER WIDE MISSILE TESTS:** Work is under way at the Propulsion Directorate to host testing in support of the Navy Theatre Wide (NTW) Missile Defense System Program. These NTW Kinetic Warhead System Integration Tests will be conducted at the National Hover Test Facility (NHTF) at Edwards AFB, California. The NHTF supports the development and demonstration of missile defense system sensor/seeker packages by permitting free-flight evaluation of performance in a controlled environment. All outstanding facility preparations for the NTW tests have been completed. These preparations included long duration testing of the Kinetic Warhead environmental control box, repair of the target background, checkout procedures for all critical systems, and installation of an intrusion detection system. The device and the test team will arrive in early May, and testing will follow in June and July. The NTW Program strives to provide an upper-tier, sea-based capability to counter medium and long-range theater ballistic missile threats as they pass through the exo-atmospheric region. NTW missiles will be deployed aboard Aegis-equipped ships and will provide cost-effective and timely response to the current threat by leveraging on the Navy’s existing and planned Aegis fleet. (L. Quinn, AFRL/PRR, (661) 275-5630)

**THRUST MEASUREMENTS FOR MICROPROPULSION:** A unique thrust stand capable of measuring the minute thrust of the Free Molecule Micro-Resistojet (FMMR) has been successfully demonstrated by the Propulsion Directorate’s Aerophysics Branch (AFRL/PRSA) and the University of

Southern California. The thrust stand was developed in support of the FMMR flight experiment which is to be flown on a microsatellite being built by Arizona State University (ASU). The thrust stand incorporates innovations that employ the FMMR's operating characteristics to advantage in measuring very low thrust levels. The stand is currently capable of measuring thrust levels as low as  $35\ \mu\text{N}$  (about eight millionths of a  $\text{lb}_f$ ) with an error of  $\pm 10$  percent, and measurements of an order of magnitude lower thrust ( $\sim 5\ \mu\text{N}$ ) should be possible in the near future. The ASU microsatellite will be one of three university satellites making up the Three Corner Satellite Constellation, which has the goals of demonstrating stereo imaging, virtual formation operations, cellular-phone communications, and innovative command and data handling. The ASU microsatellite has the additional goal of demonstrating a safe and simple micropropulsion system. The FMMR addresses these micropropulsion needs, and it will be demonstrated in space through orbit raising and de-orbiting maneuvers. The launch of this AFOSR/DARPA sponsored flight is scheduled for late 2002. (A. Ketsdever, AFRL/PRSA, (661) 275-6242)



The FMMR thrust stand

YERKES APPOINTED VISITING SCHOLAR: Dr. Kirk Yerkes of the Propulsion Directorate's Power Generation & Thermal Management Branch (AFRL/PRPG) has been appointed a Visiting Scholar in the Department of Mechanical Engineering at the University of California-Berkeley. This appointment recognizes Dr. Yerkes research work with fluid micro-capillary pumped loops (micro-CPL) which function as heat exchangers for cooling electronic devices. This work has yielded the

operation of the world's smallest known CPL. The evaporator for this device measures approximately 400 by 1000 microns and has line diameters ranging from 100 to 400 microns. Dr. Yerkes provided initial analysis of the micro-CPL with professors at Berkeley, collaborated on fabrication methods, established testing methods locally at PRPG laboratory facilities, and transferred the results to the Berkeley team for its use. His appointment as a Visiting Scholar is for the period 3 September 1999 to 31 December 2000. (S. Rubertus, AFRL/PRPG, (937) 255-6241)



Dr. Kirk Yerkes

#### ADVANCING LIFE PREDICTION METHODOLOGY:

Current manufacturing techniques use laser shock peening to impose residual stresses in component surfaces. However, life prediction methods do not use this benefit against crack growth when determining component life. Under sponsorship of the Propulsion Directorate's Turbine Engine Division (AFRL/PRT), Research Applications, Inc has started an effort to address this shortcoming in the current prediction methodology. In this effort, Research Applications will develop and validate a marketable methodology for advanced life prediction and residual stress management of turbine engine components under actual service conditions. Advanced methodology is needed for life extension of existing engine components, for enhanced safety of future aircraft engines, and for rational management of life cycle costs. Research Applications will work closely with Honeywell on design aspects of life prediction, and Lambda Research will be a subcontractor for laboratory experimentation. Better life prediction methods will result in fewer aircraft losses and reduce unnecessary replacement costs. (Lt B. Beachkofski, AFRL/PRTC, (937) 255-4826)

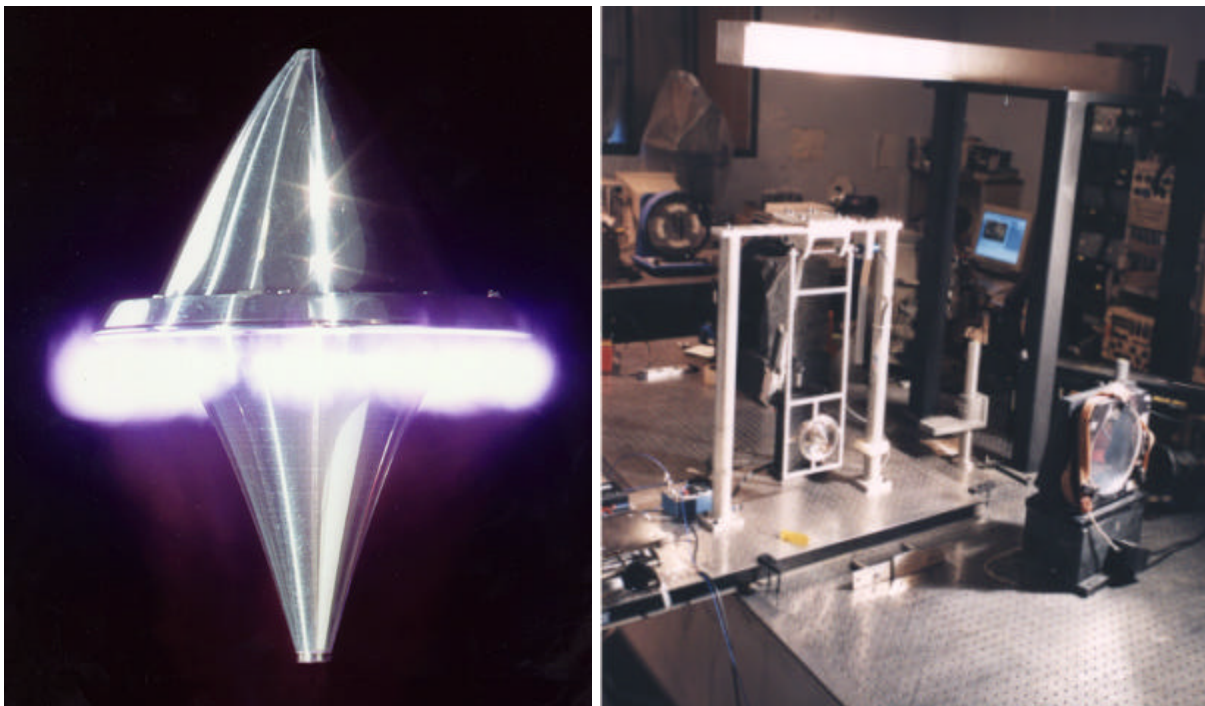


Dr. Nelson Forster

FORSTER NAMED STLE FELLOW: Dr. Nelson Forster of the Propulsion Directorate's Lubrication Branch (AFRL/PRSL) was recently named a Fellow in the Society of Tribologists and Lubrication Engineers (STLE). Of the STLE's membership of more than 4,600 individuals, Dr. Forster was one of only four to be elevated to the status of Fellow in 2000. Dr. Forster currently serves as the Air Force senior engineer responsible for the technical direction of research and development for mechanical and lubrication systems in gas turbine engines. He was recognized by STLE for his significant and continuing contributions to advance the basic understanding and technology in high temperature lubrication. Dr. Forster was also honored in 1999 as the recipient of STLE's Captain Alfred E. Hunt Award for the best paper published in a Society publication. Additionally, he is a former winner of the prestigious Harold Brown award; the Air Force's highest award for the application of engineering science to field related problems. Our

heartiest congratulations go out to Dr. Forster on this well-deserved distinction. (R. Wright, AFRL/PRSL, (937) 255-5568)

LIGHTCRAFT LASER TESTED AT GREATER DISTANCES: Researchers from the Propulsion Directorate and NASA Marshall Space Flight Center recently gathered in the New Mexico desert for testing of laser-propelled Lightcraft vehicles. This futuristic concept of propelling a vehicle with a beam of laser light is envisioned as a low cost method for placing small satellites into orbit. Recent tests were carried out at the High Energy Laser System Test Facility (HELSTF) at White Sands Missile Range (WSMR) between 22-26 February 2000. Performance tests were conducted with single pulses from a 10 kW CO<sub>2</sub> laser. These tests were conducted over a range of pulse energies and at distances ranging from 10 to 500 feet from the telescope optics. These were the first long-range tests in the laser's "far" field as all previous performance measurements had been conducted at short distances in the laboratory. Demonstrating the performance of the laser propulsion system at increasing distances is a key step to achieving Lightcraft goals. All tests were conducted using a thin ring of ablative polymer propellant (Delrin®) which was inserted and bonded inside the shroud. PR personnel conceived, fabricated, assembled, and checked-out a modified pendulum impulse test stand to perform these tests. Preliminary results indicate that performance in the far field increased by a factor of 2 to 3 over that obtained in the laboratory. While data reduction is still ongoing, it appears that the diffracted laser beam, which is spread out and completely fills the Lightcraft optical surface, outperforms the highly confined near field beam. It is postulated that ablation is more uniform and a greater mass of propellant gas is heated with the diffuse beam, thus producing more thrust than a narrow near field beam. (F. Mead, AFRL/PRSP, (661) 275-5929)



A Lightcraft model (left) and the PR developed pendulum impulse thrust stand (right)

NEW THERMAL MANAGEMENT SOFTWARE DELIVERED: For the past seven years, Lockheed Martin (Fort Worth) has been developing proprietary modeling software to enable the rapid evaluation of new thermal management and secondary power systems for aerospace platforms. The Integrated Thermal Management System (ITMS) computer program has been used extensively by Lockheed Martin's power subsystem engineers, and has recently assisted with F-22 Raptor EMD modifications. Lockheed Martin and the Air Force Research Laboratory (AFRL) established an agreement about a year and a half ago to allow a limited number of ITMS software copies to be used by government personnel at no cost. The Propulsion Directorate's Power Division (AFRL/PRP), in turn, funded Lockheed Martin to make several enhancements to ITMS to increase its utility. This enhanced version of ITMS (v4.8) has recently been delivered and is now available for in-house use by DoD personnel. The ITMS program includes several standard thermal system components such as heat exchangers and turbines and adds the ability to include user-defined component performance maps that can match the component(s) to the various flight conditions of an aircraft mission. The ITMS Program also allows a user to call user-defined or legacy codes. (B. Donovan, AFRL/PRPG, (937) 255-6241)



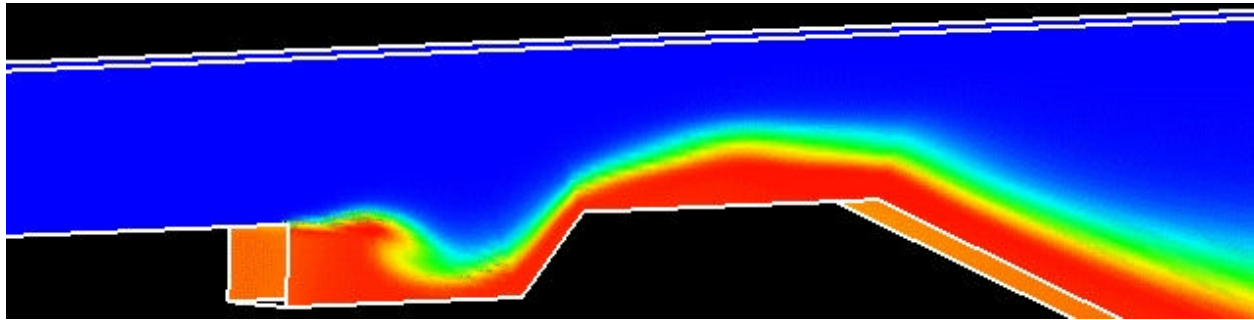
Wear metal debris - first image taken by new X-ray imaging technique

POTENTIAL BREAKTHROUGH IN MICRO-IMAGING: Researchers working for the Propulsion Directorate's Lubrication Branch (AFRL/PRSL) have made a possible breakthrough in micro-imaging. These researchers, on-site contractors with the University of Dayton Research Institute (UDRI), have shown the feasibility of using a small charged-coupled device (CCD) camera system to view particles or other targets with high resolution. This discovery was a fortuitous byproduct of work to develop a small, inexpensive X-ray fluorescence (XRF) spectrometer for identifying bearing wear debris particles caught on the head of

magnetic chip detectors. The visual imaging capability was demonstrated by capturing the image of metal filings on film. The image was scanned and the particle size and area were calculated. Particles down to 50 microns (about two-thousandths of an inch) could be detected and sized. This visual technique should provide a measure of the relative size and number of particles, and even more noteworthy, the researchers believe that it may also be possible to obtain an X-ray image from the XRF unit that could then be scanned and processed. Incorporation of the imaging system with the XRF unit is in the developmental stage, and will require identification of some fluorescent screen materials that might work with a CCD camera. Efforts are under way to determine the advantages of this type of approach for XRF and numerous other applications. (R. Wright, AFRL/PRSC, (937) 255-5568)

FIRST FULL-SCALE COMBUSTOR APPLICATION OF CFD++: An unstructured computational fluid dynamics code (CFD) is being applied to scramjet combustor design for the first time by

researchers in the Propulsion Directorate's Combustion and High Speed Systems Branch (AFRL/PRSC). Metacomp Technologies, Inc developed the code, CFD++, under Small Business Innovation Research (SBIR) and Dual-Use Applications Program (DUAP) funding. CFD++ has many features that allow it to converge on solutions extremely rapidly for mixed transonic/supersonic/subsonic flows. Several new features in the code make it appealing for very large problems, and the addition of a PRSC developed hydrocarbon combustion model makes combustor simulations practical. The new combustion model has proved to be very efficient and stable, and it avoids some common problems associated with other combustion models. Results from a prior calculation using a different code, which matched experimental data fairly well, are being used for calibration of the new combustion model. Remarkably, a solution was obtained in only a few days using the new combustion model with CFD++, and this time included learning the code and inputting the model. This same task would have taken several weeks with other models. Due to the ease and speed with which solutions can be obtained using CFD++, such computations may have a greater effect on component design efforts and alleviate the need for time/cost intensive testing. (D. Davis, D. Risha, and M. Hagenmaier, AFRL/PRSC, (937) 255-1233)



Reaction product mass fraction contours computed by CFD++

TESTING OF ADVANCED TURBOPUMP CONTINUES: Test 18 of the Advanced Liquid Hydrogen (ALH) Turbopump was recently completed. Pratt & Whitney (P&W) Liquid Space Propulsion developed the ALH Turbopump under a program with the Propulsion Directorate's Rocket Propulsion Division (AFRL/PRR). The turbopump was developed in support of the 50K Expander Cycle Integration and Test contract that serves as the Integrated High Payoff Rocket Propulsion Technology (IHPRT) Phase I Upper Stage Demonstrator. This effort will integrate the fuel turbopump and thrust chamber assembly hardware to feed into a high-pressure expander cycle testbed engine. The performance of the turbopump is critical, as generating high chamber pressure is the primary factor to increase engine performance. This particular test was a qualified success, as the pump spun up to 107,000 rpm and achieved an outlet pressure of 1380 psi. Unfortunately, post-test inspection showed that the rotor and bearing set were destroyed. Analysis of this failure is under way, but no firm conclusions as to the reason for the failure have been reached. Future plans for the program are also being examined, and these plans may include redesign of substantial elements of the turbopump. (L. Quinn, AFRL/PRR, (661) 275-5630)

MONOPROPELLANT WORK FOR ICBM SPO COMMENCES: The Propulsion Directorate's Propellants Branch (AFRL/PRSP) is conducting research on advanced monopropellants for the ICBM System Program Office (SPO) at Hill AFB, Utah. This monopropellant research supports the ICBM SPO's mission of developing, acquiring, and supporting silo-based ICBMs. This work is in pursuit of so-called "Phase IV" monopropellants, which would be the highest performance monopropellants ever developed with performance significantly exceeding Integrated High Payoff Rocket Propulsion Technology (IHPRT) Phase III monopropellant goals. Recent work has focused on the estimation of critical diameter of a monopropellant (RK-315A) with volumetric impulse nearly 100 percent greater than hydrazine. It is naturally desirable for a monopropellant to possess a large critical diameter, and liquid propulsion system developers generally require a minimum of 0.75-inch confined critical diameter for monopropellants. Consequently, a 0.75-inch critical diameter evaluation was performed on a sample of RK-315A. The test was successfully conducted and the velocity measurement of the shock wave through the propellant verified the inability of the propellant to support a detonation wave. Thus, RK-315A meets the critical diameter requirement generally applied to monopropellants. Work in the near-term will continue to focus on additional evaluations of safety characteristics of the monopropellant. (T. Hawkins, AFRL/PRSP, (661) 275-5449)

INITIAL TESTING OF AADC JETEC DEMONSTRATOR CONCLUDES: Initial testing of the Allison Advanced Development Company (AADC) Phase II Integrated High Performance Turbine Engine Technology (IHPTET) Joint Expendable Turbine Engine Concept (JETEC) demonstrator engine has concluded. The objective of the performance test was to demonstrate the Phase II supersonic JETEC specific thrust goal. The supersonic engine was designed to demonstrate such technologies as lamilloy vanes, single crystal CMSX-4 Castcool turbine blades, high temperature exhaust nozzle, high-pressure turbine structural rod, and high temperature bearing with impact damper. Initial start and shakedown testing were successfully accomplished. Then during a slow acceleration to 88 percent corrected rotor speed, a pronounced change in engine vibration was observed. A review of the data showed no obvious cause for the vibration, and the test was repeated. Upon a slow acceleration to 88 percent corrected speed, vibration sensor levels exceeded the transient limits, and the engine was decelerated to idle. During deceleration the vibration levels continued to exceed acceptable levels, and the engine was shut down. Post-test examination indicated a rub had occurred with distress to the turbine rotor blades, blade track, number two bearing, and the third and fourth compressor stage blade tips. Total run time was 4 hours and 31 minutes including 37 minutes of hot time. An engine disassembly and investigation as to the cause of the vibration was conducted. A teardown review with the government presented the investigation findings. Inadequate lubrication of the bearing progressed into loss of internal radial clearance, followed by rapid heating and wear (grooving) of the inner race. The groove resulted in rotor radial shift. AADC is preparing a proposal addressing a potential rebuild of the demonstrator engine for either IHPTET Phase II or III. (B. Newman, AFRL/PRTP, (937) 255-2767)